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Excitation Functions for some Reactions Induced by ^{11}B on Light Elements*

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Abstract

The yield curves and the excitation functions for 5 nuclear reactions on lithium, beryllium, boron, magnesium and silicon were determined in the 6 to 32 MeV ^{11}B energy range. The best yield was obtained with the $^{9}Be(^{11}B, 2n)^{18}F$ reaction. The maximum cross section for this reaction was calculated to be 130 ± 20 mb for a 17 MeV ^{11}B ion beam.

Introduction

Charged particle activation analysis is well recognized as an outstanding analytical tool for determining traces of light elements [1]. Lately, the development of heavy ion beams has further enriched the range of nuclear reactions available for analytical purposes [2, 3]. In a recent paper [4], we have discussed the analytical potential of the ^{11}B ion beam and shown that the $^{6,7}Li(^{11}B, ^{1,2}H)^{16}N$, $^{9}Be(^{11}B, 2n)^{18}F$, $^{10,11}B(^{11}B, ^{1,2}H)^{20}F$, $^{24,25,26}Mg(^{11}B, \alpha xn)^{30}P$ and $^{28,29,30}Si(^{11}B, \alpha xn)^{34m}Cl$ reactions allow a selective, sensitive and nondestructive determination of these light elements. The aim of the present study was to calculate the kinematic parameters and to determine the excitation functions for the above reactions induced with ^{11}B energies ranging from E_{lab} = 8 MeV to E_{lab} = 35 MeV. These data are important for selecting the optimum experimental conditions for analytical applications. They also allow the calculation of the average activation energy used in the calibration method described by ISHII *et al.* [5].

Experimental

Irradiation

Beams of ^{11}B at various energies and charge states were obtained with the HV EC-EN Tandem Van de Graaff accelerator of the Institute for Medium Energy Physics at the Swiss Federal Institute of Technology in Zürich. The ^{11}B ions were produced by sputtering a solid boron cone with cesium atoms.

Two different irradiation chambers were used depending on the half-life of the radionuclide of interest.

The first one, especially designed for determining the production yields of short lived radionuclides, has been described in an earlier paper [6]. The mobile target holder allowed cyclic irradiations and radioactivity measurements without interruption of vacuum (10^{-5} mm Hg). The beam current was monitored immediately after the measurement of the sample activity by using a Faraday cup placed directly behind the position of the irradiated target.

The second chamber was equipped with a water-cooled target holder with two Ta collimators up stream from the target to improve the beam parallelism. The beam current was monitored during the sample irradiation using a small wire mesh placed between the two collimators. The grid transmission was determined with a Faraday cup inserted in place of the target.

Detection

Two detection systems were used. To detect the relatively long lived ^{34m}Cl, ^{30}P, and ^{18}F, the irradiated targets were mounted on a CEA (Commissariat à l'Energie Atomique, France) source holder between two thin polyethylene foils and placed in an aluminum box with a wall thickness chosen to maximize the yield of the 511 keV γ-rays from the positron annihilation. A 12 position automatic sample changer for coincidence measurements equipped with two 3″ × 3″ NaI (Tl) scintillation detectors (QUARTZ & SILICE, Scintibloc 76/S/76) was used for counting the 511 keV radiation of the samples. The absolute counting efficiency was determined to be 8.5% using a standard ^{22}Na source.

A coaxial Ge(Li) detector (ORTEC 8001–1020 V, 2.0 keV resolution at 1.33 MeV) was used to detect the γ radiation emitted by ^{16}N and ^{20}F, through a thin plexiglass window attached to the irradiation chamber. The detector was linked to a multichannel analyzer (CANBERRA 80). The whole cycle (irradiation – activity measurement – beam monitoring) was electronically controlled and repeated for at least 10 cycles. At the end of the final counting the total spectrum was transferred to a floppy disc recorder (SCIENTIFIC MICRO SYSTEM, D222) for further analysis with a PDP 11/23 computer. The absolute detection efficiency for the 1634 keV γ-rays of ^{20}F was determined to be $(2.6 \pm 0.1) \times 10^{-3}$ in our counting conditions, using a ^{152}Eu standard source. In the case of ^{16}N, the detector's efficiency was estimated to be $(5.5 \pm 0.5) \times 10^{-4}$ at 6128 keV as suggested by SEYFARTH *et al.* [7].

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* *Dedicated to Prof. P. Lerch for his 60th birthday*

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Targets

The five elements investigated were irradiated as pure metallic foils (Be, 99.8%, GOODFELLOW METALS, Ltd.; Si, > 99%, Inst. Microélectronique-EPFL) or as p. a. compounds of well known stoechiometry (LiF, 99.9%, MERCK AG.; H_3BO_3, 99.9%, MERCK AG.; MgO, 97%, MERCK AG.). The powder was pressed in small discs of 13 mm diameter and 1–3 mm thickness. All targets were thicker than the range of the incident ions.

Cross sections calculation

The excitation functions, $\sigma(E)$, were derived from the experimental reaction yield curves, $Y(E)$, which themselves correspond to the measured activity of the radionuclide of interest as a function of the ion beam energy. The stopping power, dE/dx, of the irradiated target [8] was also taken into account:

$$\sigma(E) = \frac{1}{n}\left(\frac{dY}{dE}\right)_E \left(\frac{dE}{dx}\right)_E$$

where n is the concentration of atoms (at $\cdot g^{-1}$) from which the radionuclide of interest is formed.

Depending on the mode of irradiation (single or cyclic), the activity at the end of irradiation was determined directly [9] or using the total number of counts detected in the γ-line of interest [10] after the summation of the consecutive spectra.

Results and discussion

The catalogue of nuclear reactions investigated which are induced by bombarding lithium, beryllium, boron, magnesium and silicon, with the ^{11}B ion beam is presented in Table 1. Also listed in Table 1 are the reactions Q-values and Coulomb barrier (E_c). Only beryllium has one single natural isotope. Lithium and boron occur as ^{6}Li and ^{7}Li, ^{10}B and ^{11}B respectively. In these latter cases, based upon the calculation of the reaction kinematic parameters, it was not possible to determine which isotope was responsible for the production of ^{16}N and ^{20}F. The same remark applies for the production of ^{30}P and ^{34m}Cl by the reactions of ^{11}B ions on magnesium and silicon respectively. There is, however, a slight difference in this case as the $^{24}Mg(^{11}B, \alpha n)^{30}P$ and $^{28}Si(^{11}B, \alpha n)^{34m}Cl$ reactions are distinguishable from the other possible reactions on ^{25}Mg and ^{26}Mg, respectively ^{29}Si and ^{30}Si, by their exoenergetic characteristics. Furthermore, ^{24}Mg and ^{28}Si are the most abundant isotope of each element (78.99% ^{24}Mg and 92.23% ^{28}Si). Finally, as the reactions yielding the emission of more than two particles present usually very small cross-sections at low energies, one could assume that ^{24}Mg, respectively ^{28}Si, are most likely responsible for the formation of ^{30}P and ^{34m}Cl. But as the reactions have not been tested separately with pure isotopes, the production yields obtained here must be considered as corresponding to the formation of one radionuclide by different nuclear reactions.

The characteristics of the radionuclides produced are also given in Table 1. Owing to the short half-life and to the γ-ray emissions of ^{16}N and ^{20}F, the measurements of their production yields were undertaken using the cyclic activation set-up, which yields better statistics [11]. The ^{18}F, ^{30}P, and ^{34m}Cl radionuclides were produced with a single irradiation and their activity was determined by coincidence measurements.

For each reaction, the experimental activation curve, obtained by reporting the yield as a function of the incident beam energy, was refined using a computer program [12]. Thus, the yield curve was expressed as a polynomial function of the 4th order by least square fitting. These curves are presented in Figure 1; in order to facilitate their comparison, the yield scale is logarithmic. On a

Table 1. Kinematic parameters of the reactions and characteristics of the products

Reaction	Q (MeV)	E_c (MeV)	Radionuclide produced		
			$T_{1/2}$	E_γ (keV)	γ-rays intensities
$^{6}Li(^{11}B,p)^{16}N$	9.7	10.1	7.13 s	6128	0.69
$^{7}Li(^{11}B,d)^{16}N$	4.7	9.0		5617 5106	P P
$^{9}Be(^{11}B,2n)^{18}F$	3.0	10.8	110 mn	511	1.93
$^{10}B(^{11}B,p)^{20}F$	13.4	11.5	11.4 s	1634	1.00
$^{11}B(^{11}B,d)^{20}F$	4.2	10.8		1122 611	P P
$^{24}Mg(^{11}B,\alpha n)^{30}P$	3.5	16.4	2.5 mn	511	2.00
$^{25}Mg(^{11}B,\alpha 2n)^{30}P$	− 1.9	16.1			
$^{26}Mg(^{11}B,\alpha 3n)^{30}P$	−13.4	15.8			
$^{28}Si(^{11}B,\alpha n)^{34m}Cl$	0.2	17.8	32 mn	511	1.28
$^{29}Si(^{11}B,\alpha 2n)^{34m}Cl$	− 7.2	17.5		145	0.35
$^{30}Si(^{11}B,\alpha 3n)^{34m}Cl$	−17.9	17.2		1177	0.14
				2128	0.48
				3305	0.11

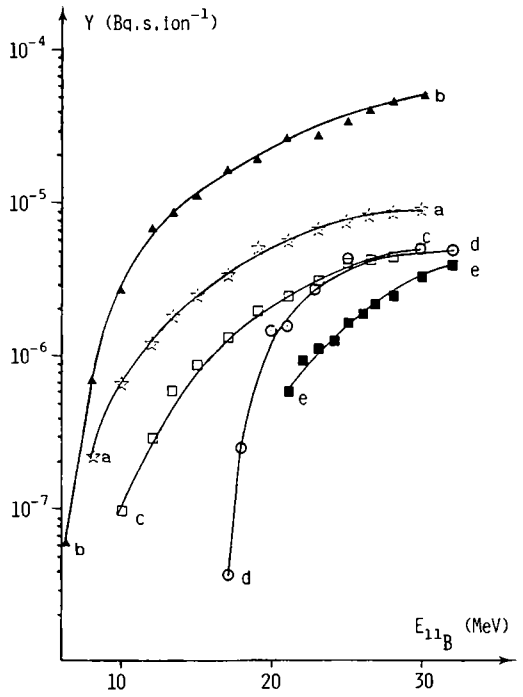

Fig. 1. Yield curves of the reactions
a. $^{6,7}Li(^{11}B, ^{1,2}H)^{16}N$, b. $^{9}Be(^{11}B, 2n)^{18}F$,
c. $^{10,11}B(^{11}B, ^{1,2}H)^{20}F$, d. $^{24,25,26}Mg(^{11}B, \alpha xn)^{30}P$,
e. $^{28,29,30}Si(^{11}B, \alpha xn)^{34m}Cl$

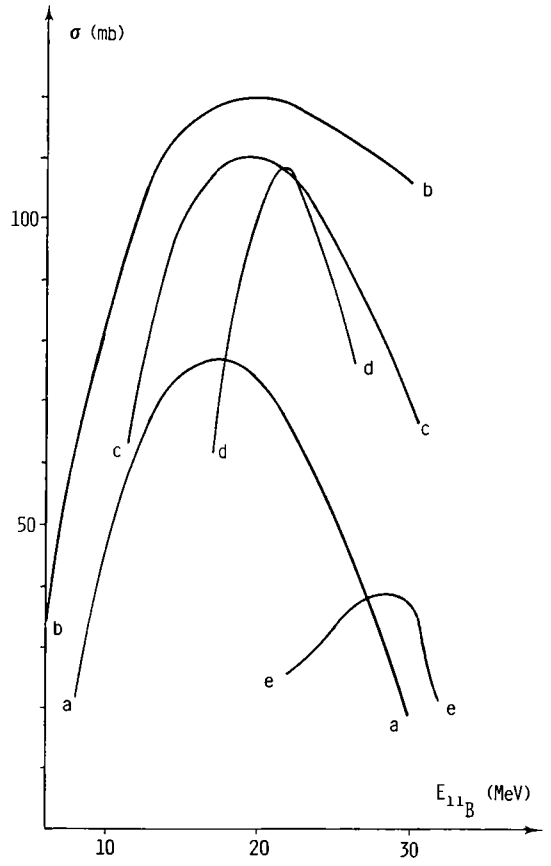

Fig. 2. Activation cross-sections of the reactions
a. $^{6,7}Li(^{11}B, ^{1,2}H)^{16}N$, b. $^{9}Be(^{11}B, 2n)^{18}F$,
c. $^{10,11}B(^{11}B, ^{1,2}H)^{20}F$, d. $^{24,25,26}Mg(^{11}B, \alpha xn)^{30}P$,
e. $^{28,29,30}Si(^{11}B, \alpha xn)^{34m}Cl$

linear base, all the curves show an inflexion point, indicating a maximum cross-section. While the yields for ^{18}F and ^{20}F still increase beyond 30 MeV ^{11}B, the production of ^{16}N, ^{30}P, and ^{34m}Cl reaches a plateau around this latter beam energy. The errors on $Y(E)$ are estimated to range between 3% and 5% depending on the reactions studied.

The derivative of these yield curves, dY/dE, at a given beam energy led to the cross-section calculations. The excitation functions are presented in Figure 2. The maximum cross-section values are reported in Table 2, together with the corresponding incident beam energy, which increases with the atomic number of the element. The errors on the cross-sections are estimated at 20%; however, in the case of the $Mg(^{11}B, \alpha xn)^{30}P$ reaction, this error is larger ($\sim$ 40%) because of the mode of irradiation and the relative short half-life of the product, which hinder the precision of the activity measurements.

Table 2. Maximum cross-sections

Reaction	Energy (MeV)	Cross-section (mb)
$^{6,7}Li(^{11}B, ^{1,2}H)^{16}N$	17	78 ± 15
$^{9}Be(^{11}B, 2n)^{18}F$	17	129 ± 26
$^{10,11}B(^{11}B, ^{1,2}H)^{20}F$	19	112 ± 22
$^{24,25,26}Mg(^{11}B, \alpha xn)^{30}P$	21	108 ± 42
$^{28,29,30}Si(^{11}B, \alpha xn)^{34m}Cl$	28	39 ± 8

The cross-section values do not always correlate proportionately with the sensitivity of a given reaction applied for analysis. For instance, the production of ^{34m}Cl leads to the same detection limit for silicon as ^{16}N or ^{20}F for lithium or boron respectively. On the other hand, the $^{9}Be(^{11}B, 2n)^{18}F$ reaction provides a very sensitive trace beryllium determination, as one would expect based on its large cross-section and the propitious positron emission of ^{18}F.

Conclusion

The determination of these excitation functions facilitates the choice of the optimum experimental conditions when applying the reactions investigated for analytical purposes. The cross-section values indicate that a sensitive determination of lithium, boron, magnesium and silicon can be expected using this activation technique. A particularly sensitive trace determination of beryllium is also possible [13]. Finally, due to the short half-lives of ^{16}N and ^{20}F, a fast and simultaneous trace determination of lithium and boron can be undertaken nondestructively [4].

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